Experimental set-up for testing active and passive systems for energy savings in buildings – Lessons learnt

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Abstract

This paper describes a building prototype experimental set-up used for testing active and passive systems for energy savings, presenting the used methodology, reviewing the main experimental results and identifying limitations. The test facility is located in Puigverd de Lleida (Spain) and has been experimentally evaluating different materials, technologies and systems which might be integrated in building design to provide energy savings for space heating and cooling since 2002. The research fields of passive technologies covered the effect of using different insulating materials, construction systems based on sustainable materials, addition of phase change materials in building envelopes and green infrastructures such as green roofs and walls. On the other hand, the active systems tested were focused in exploiting different available renewable energy source available, such a solar thermal, free-cooling with night air, or geothermal heat, using thermal energy storage systems to shift the heating and cooling loads.

Keywords: energy savings; active systems; passive systems; buildings; phase change materials (PCM); experimental set-up.

1. Introduction

The high energy consumption of the building sector has been identified as a key issue in the worldwide energy scenario and has modified important energy policies and legislations [1]. These new policies restrict the use of primary energy sources for heating and cooling and stimulate the use of renewable energies in the sector, which supposes an important challenge for architects and engineers all over the world. Within this context the research and innovation are crucial to introduce new technologies in the building sector [2.

Numerical simulation based on Building Energy Simulation Tools (BEST), such as Energy Plus or TAS, which are commonly used during the design phase of buildings, are also used to investigate the performance of different construction systems, technologies or building materials [3 4. In addition, experimental measurements at lab scale have been widely used to characterize the thermal resistance [5 sound insulation [6 or fire resistance and mechanical properties [7 of different new materials. Moreover, testing at lab scale has been also used to analyse the thermal performance of different systems [8 9.

Nevertheless, experimental measurements under real environmental conditions are required not only to validate numerical models but to convince the building sector in applying and using the new developed technologies. In this sense, some researchers have implemented their systems in already existing buildings to demonstrate their performance [1011. This experimental approach provides important and useful information since it tests the developed new materials, systems and technologies when are included in real building application. However, it is usually difficult to evaluate the effect of the new installed technology in detail and distinguish the specific contribution of the new installed technology from the whole performance of the building. Moreover, the required cost investment for this experimental approach is usually very high and unaffordable during the testing phase of the technologies, especially for those with a technology readiness level (TRL) [12 below 8.

In this context, experimental building prototypes have become popular to test and compare the performance of materials and systems under real conditions, without the high costs associated with experimentation using real buildings, and the ability of isolating the variable or group of variables which are the scope of research. Revel et al. [13 used four building prototypes located in Madrid (Spain) to test the performance of cool coloured ceramic tiles, acrylic paints and bituminous membranes for building envelopes. Mandilaras et al. [14 compared the performance and thermal resistance of a Vacuum Insulation Panels (VIP) against expanded polystyrene (EPS) in a two-storey prototype building located inside the campus of the National Technical University of Athens (Greece).

Furthermore, apart from comparison studies, house-like prototypes have been used to study different specific technologies and methodologies. Albatici et al. [15 used a house-like prototype to validate the use of quantitative infrared thermography in evaluating the thermal transmittance in steady state of building envelopes. In addition, Li et al. [16 tested the performance of a solar thermal curtain wall under real conditions and Li et al. [17 demonstrated experimentally the influence of windows films on the overall building energy consumption.

As shown from literature, due to high cost of investment and maintenance, the set-ups containing experimental building prototypes are usually focused on testing specific technologies. An exception to this can be found in the experimental set-up located in Puigverd de Lleida (Spain) (Figure 1). This set-up contains 22 house-like cubicles and has been testing building passive and active systems since 2002. The experience and lessons learnt during the different experimental campaigns are compiled and presented in this paper. Moreover, several problems and limitations have been found during the different experimental campaigns carried out in the facility, which are identified and addressed.

Figure 1. Experimental set-up in Puigverd de Lleida (Spain)

2. Methodology

2.1 Overview of the experimental set-up

The experimental set-up located in Puigverd de Lleida has been used for testing both active and passive systems for energy savings in buildings under continental-Mediterranean weather conditions, Csa (warm temperate, dry and hot summer) according to Köppen-Geiger climate classification [18. A sketch of the facility and the distribution of the 22 cubicles are shown in Figure 2.

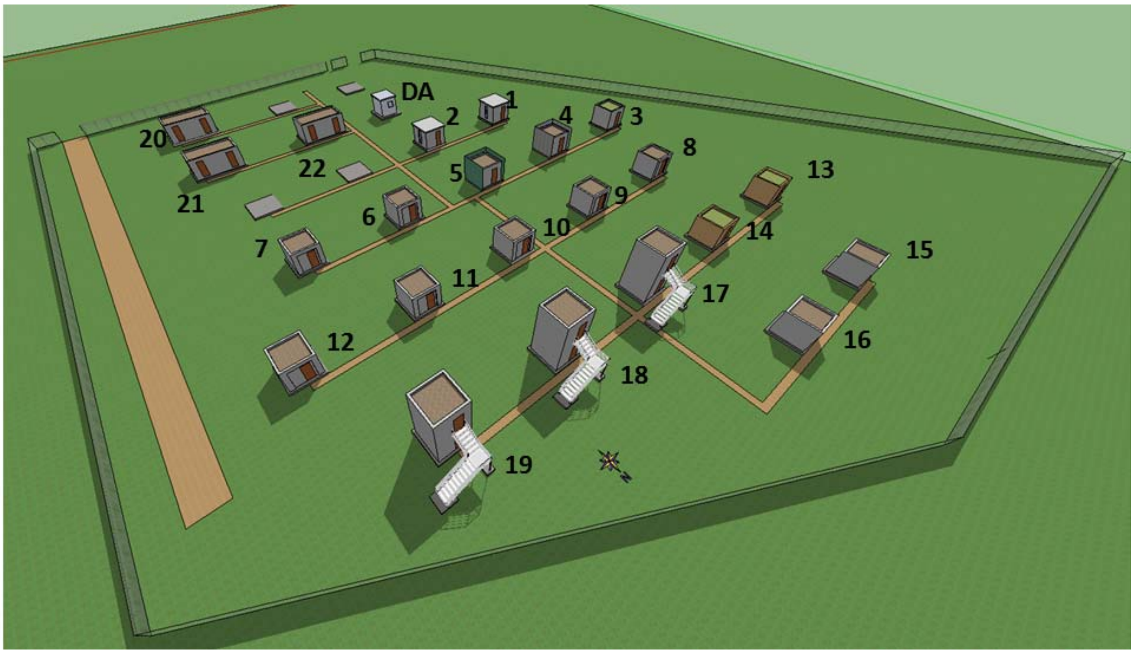


Figure 2. Lay-out sketch of the experimental set-up

Since it has been previously stated, the experimental facility is used for testing different building construction systems, materials and technologies. The facility consists of 16 different single cubicles with same inner dimensions (2.4 m x 2.4 m x 2.4 m), 3 double-height cubicles (2.4 m x 2.4 m x 5.1 m) and 3 double width-cubicles (2.4 m x 5.25 m x 2.4 m). The experimental methodology for testing both active and passive technologies is based on comparative studies. This methodology allows the evaluation of the effect of each technology in the thermal and energy performance of the house-like cubicle in comparison to a reference cubicle, which is built identically as the previous but without the tested technology. Even though all envelopes and some roofs are different, the foundation consists in all cases of a reinforced concrete slab of 3 x 3 m with a gravel drainage layer.

Four different construction phases over this period have formed the current available facility. During the first construction period, in 2002 and within the European FP6 project MOPCON, two identically shaped house like cubicles (1 and 2 from Figure 2) were built to test the effect of adding micro-encapsulated phase change material (PCM) into pre-fabricated concrete panels. Hence, according to the comparative methodology, one house-like cubicle was built with conventional concrete and the other one with concrete with microencapsulated Micronal® PCM from BASF. These two cubicles are the only ones in the set-up provided with windows, since it was measured that the effect of direct solar radiation in such small spaces were dominant and difficult the correct evaluation of the different systems.

The second construction period was on 2007, when seven house like cubicles (8 to 12, 15 and 16 from Figure 2) were built to test different passive techniques such as the use of different insulations (polyurethane, mineral wool and polystyrene), the use of sensible thermal mass, and the use of macro-encapsulated PCM. Moreover, during the third construction phase in 2009, seven single cubicles (3 to 7, 13 and 14 from Figure 2) were built to study the effect of green roofs and vertical greenery systems, the performance of rammed earth construction systems, and to test the use of new developed insulations. In addition, during this construction phase, three double height cubicles (17 to 19 from Figure 2) were built to test a ventilated double skin facade and an active slab with PCM (within the national project MECLIDE and followed up in INPHASE), and two double width cubicles (20 and 21 from Figure 2) which were used to test the incorporation of shape stabilized PCM layer with thermal and acoustic properties (within the project RESCONFORT and followed up in the European FP7 project REWASTEE). Finally, the fourth construction phase incorporated to the facility a double width cubicle (22 from Figure 2) used to test a radiant wall coupled to a geothermal system

The dimensions and shape of the cubicles were selected to maximize the effect of the envelope in the performance of the building, and follows the compromise between being able to test the technologies under a realistic building scenario, and reduce as much as possible the costs related to the construction and dismantling of the building prototypes. Moreover, the orientation of all cubicles is North-South, with insulated doors and condenser units from heat pumps always facing north. Moreover, a shadow study was performed in order to ensure that all cubicles are tested as isolated building prototypes. In addition, each cubicle is provided with power supply and signal connection connected by underground paths to the data acquisition cubicle (DA from Figure 2). The data acquisition is based on several data loggers (DL01 from STEP.SL www.stepsl.com) which are connected in parallel and send signal using the RS-485 bus transmission. These devices can read 12 analogic signals (Pt-100, 4-20 mA and 0-20V) as well as read two digital signals and provide two digital outputs. Finally, a signal converter AC-250 is used to adapt the signal from RS-485 to USB.

In order to analyse the thermal performance of the different tested technologies, data is registered at five minutes interval. Several sensors are installed in each cubicle, which will be detailed in the following sections. Moreover, weather data is registered using two MIDDLETON SOLAR meters SK08 to capture horizontal and vertical global solar radiation, an ELEKTRONIK EE21 probe with a metallic shield to be protected against radiation to measure the outer air and humidity, and finally a DNA 024 anemometer for the wind speed and direction.

2.2 Passive systems testing methodology

Several passive systems have been tested in the experimental facility, following the same comparative methodology. Two different groups of experiments are performed to test these passive technologies: free floating and controlled temperature experiments. In free floating tests, no HVAC system is used to control the temperature of the cubicle, and hence, the indoor temperature and humidity of the tested cubicles are compared with its reference. On the other hand, in controlled temperature tests, a heat pump and an electrical oil radiator are used for cooling and heating. In these tests the electrical energy required to achieve a certain set point by the heat pump or the radiator is compared between cubicles. The HVAC can be connected 24 h/day or following a certain schedule in order to test the performance of the passive systems if used in a building with specific thermal requirements such as domestic or office profile. Moreover, in the controlled temperature experiments, data is analysed five days after the test has started so stable conditions in all cubicles are achieved.

The house-like cubicles used to test passive technologies are equipped with six internal wall temperatures (each wall, roof and floor) using Pt-100 DIN B probes calibrated with a maximum error of ±0.3°C, one internal ambient temperature and humidity (ELEKTRONIK EE21, accuracy ±2 %) at 1.5 m height, and two heat flux meters

HUKSFLUX HFP01 at south wall (inside and outside). Figure 3 shows the distribution of these sensors in the cubicles which are used to test passive systems.

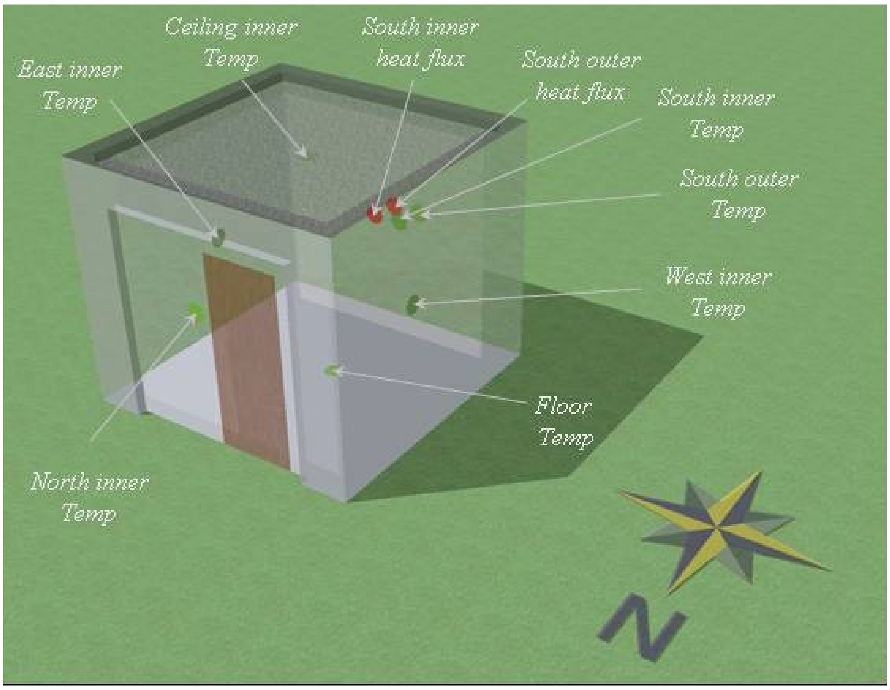


Figure 3. Sensor distribution in cubicles testing passive technologies [19

In addition, vertical greenery systems (cubicles 4 and 5) implement four extra probes by facade to measure temperatures on external wall surfaces, the air gap generated between wall and green curtain, green wall, and external air temperature at 5 cm beyond the green wall. On the other hand, rammed earth cubicles (cubicles 13 and 14) also have extra sensors in order to measure temperatures inside rammed earth walls as well as temperatures between layers in cubicle 13 (between insulation – rammed earth and coating – insulation).

Moreover, each cubicle is equipped with an electrical oil radiator (TECHNOFONT 1200 W) and a heat pump (Fujitsu Inverter ASHA07LCC) for controlled temperature tests. The electrical energy consumed by these HVAC systems is measured using an electrical network analyser (MK-30-LCD). In addition, an infrared radiator (HRM mod.301) is placed in each cubicle in order to provide internal heat gains (300 W) simulating, if desired, internal loads due to the occupancy, equipment and activity inside the building. These internal gains can be tested in both free floating and controlled temperature conditions, and they can also be programmed to follow different occupancy schedules.

2.3 Active systems testing methodology

The active systems are divided into two groups. On one side the double-height cubicles are used for testing systems implementing PCM, and on the other side, the double width cubicles are used for testing building integrated active systems.

2.3.1 Active system implementing PCM

The three double-height cubicles (17, 18 and 19 from Figure 2) are used to test the PCM active systems; one of them has a ventilated double skin facade with PCM (18), another one has an active slab as internal separation with PCM (17), and the third one has conventional construction system acting as a reference (19). Both technologies are designed to cover the cooling and heating demand of a building. A structural component of the building is used as a storage unit with an active charge and discharge process for covering the energy demand of the building. The novelty of these systems is the inclusion of phase change materials (PCM) inside the storage unit in order to increase the heat storage capacity. The cubicles are equipped with two heat pumps at different heights in order to avoid air stratification inside the room. Free floating and controlled temperature test are also done to analyse the performance of these active technologies.

The operating principles of the ventilated facade during both heating and cooling periods are shown in Figure 10. During winter, the facade acts as a solar collector during daytime, melting the macro-encapsulated PCM (SP-22) panels contained in its air cavity. Once is required by the demand, a heating supply can be provided to the room through the solidification process of the PCM (around 22ºC). On the other hand, during summer periods, the system uses low temperatures at night to solidify the PCM and provide free cooling to the room. The solidified PCM is used during daytime as a cooling supplier. Six automatized gates were installed in the openings of the facade to provide the required versatility to the system to follow the previously described operating sequences. Moreover, three fans (FCL 133 Airtecnics) were installed to provide mechanical ventilation to the system if required.

Other than the sensors used for testing passive technologies, in the ventilated facade cubicle, several sensors were installed to register surface temperature at different locations of the facade (Pt-100 DIN B), air temperature of the cavity at different heights and positions (Pt-100 with a solar shield), air velocity at inlet, outlet and mid chamber (KIMO CTV 210), pressure drop through the cavity (KIMO CP 200), PCM temperature at different positions (thermocouples Type T, 0.5 mm thick), and heat transferred to the front and back surface of PCM panels (HUKSEFLUX HFP01). Further information of this set-up can be found in de Gracia et al. [2021.

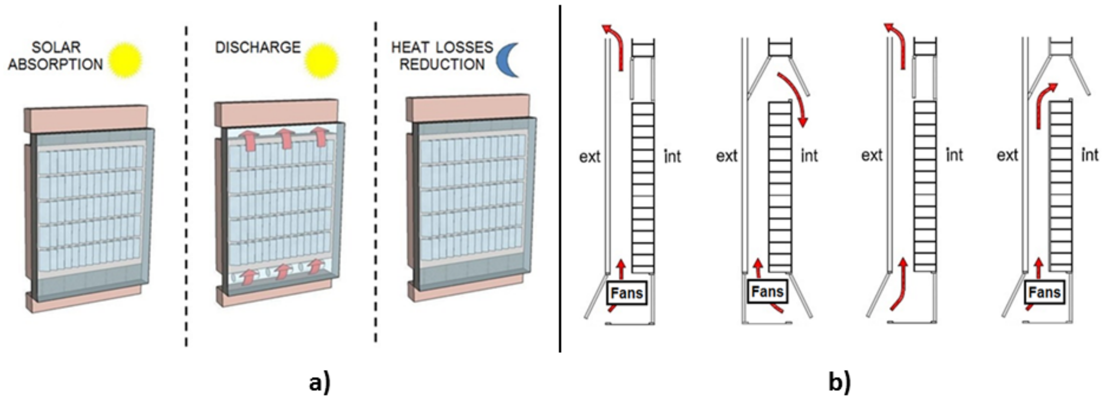


Figure 4. Operating principle of ventilated double skin facade (a) winter [20, (b) summer [21

The active slab consists of a prefabricated concrete element widely used as internal horizontal separation in new and existing buildings. The component is formed by 14 channels where the macro-encapsulated PCM (RT-21) is located in aluminium tubes. The active slab with PCM presents a similar operating principle as the ventilated facade. In winter (Figure 5a), a solar air collector provides energy to the slab to melt the PCM during daytime, this energy is stored in the melted PCM until it is required by the demand, and then discharged to the room. Furthermore, in summer (Figure 5a), the system circulates air from outdoors when temperature is lower than the melting point to solidify the PCM, and makes use of the cold stored during daytime.

An air duct installation is implemented with 6 gates (Madel CTM-AN 250x200 mm) and a fan (Sodeca CMP-512-2M) of 80 W, which allows different operational modes. The solar air collector (AIRSOL-20) is implemented in the south wall of the cubicle with the active slab and coupled to the air duct installation.

Other than the standard sensors, the whole system is instrumented by 20 additional sensors located at different strategic points of the slab with the purpose of analysing and characterizing the technology. PCM temperatures at different locations were registered inside the aluminium tubes (Pt-100 1/5 DIN B calibrated with a maximum error of ± 0.3 ºC) and air temperature and velocity were measured at the inlet and outlet of the slab (KIMO CTV210 with an accuracy of ± 0.03 m/s and ± 0.25 ºC). A detailed description of the set-up is provided in Navarro et al. [22.

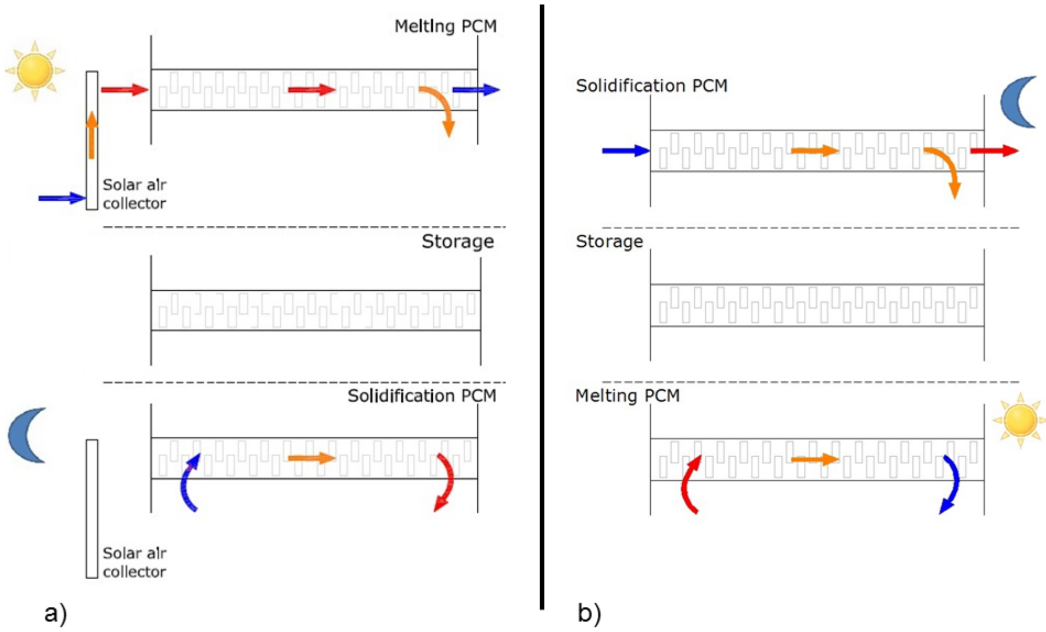


Figure 5. Operating principle of active slab (a) winter, (b) summer [22

2.3.2 <u>Building integrated active systems</u>

The three double width cubicles (20, 21, and 22 in Figure 2) are used for testing building integrated active systems. Cubicle 22 has a passive ventilated facade and a radiant wall supplied by a ground source heat pump while cubicles 20 and 21 are used as references. These last two cubicles have a conventional construction system and are equipped with conventional air-to-air heat pumps. The three cubicles have equivalent thermal transmittance in steady-state (U-value) and heavy weight walls that give them high thermal mass. The main difference is that the references only use the thermal mass passively, and in summer the walls buffer the heat gains caused by high temperatures and solar radiation, storing the heat in the wall to later release to the outdoor ambient during the night. In contrast, the radiant wall directly interacts with the building thermal mass, being able to store heat in it, which can be used for peak load shifting. Furthermore, the big heat exchange surface of the radiant wall allows achieving the heating and cooling load with a shorter temperature gradient, and thus low temperature heating and high temperature cooling is possible. On one side, this characteristic increases the efficiency of the heat pump in heating mode, as lower temperature gradient between the evaporator and the condenser leads to a better coefficient of performance. On the other side, the radiant wall enables to use free-cooling mode in summer. As high supply temperature is allowed, the ground temperature in the test site (17ºC) means that the boreholes can provide a temperature enough to provide cooling to the cubicle. This operation mode only requires the operation of circulation pumps, which consume significantly less energy than the compressor.

The radiant wall consists in polyethylene pipes embedded in the wall through vertically cut grooves, concrete was used to fill the void between the pipes and the bricks. The flow and return pipes are distributed in alternate grooves, as shown in Figure 6, to homogenize the wall surface temperature. In order to ensure equivalent flow, the radiant cubicle has five loops of identical pipe length, two in the South wall and one in each of the others. North wall can only have one loop because of the doors.

The cooling and heating demand of the radiant wall cubicle is fulfilled with an EcoGeo B2 geothermal heat pump which is coupled to two 40 m deep boreholes. This system only works as heat pump in heating mode, in cooling mode the compressor is bypassed and it works as a heat exchanger between the radiant walls and the boreholes. More details of the radiant wall cubicle can be found in Romani et al. [2324.

Figure 6. Radiant wall during the concreting phase (left) and scheme of a loop (right)

The monitoring of the radiant cubicle and its references use the same sensors than the passive cubicles. However, extra sensors are used to study the performance of the geothermal heat pump and the temperature distribution in the radiant wall. The water temperatures at different depth of the boreholes and at the return and flow pipes of both the radiant wall and the boreholes are measured with Sheathed Pt-100 DIN B calibrated with a maximum error of ± 0.3 ºC. The water flow was measured with Zenner MTKD-N pulse flow meters.

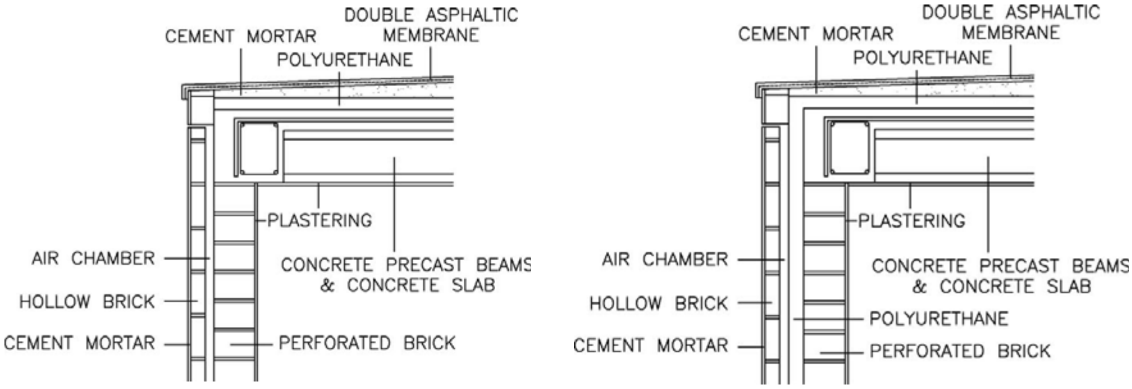
3. Results and discussion

As it was previously stated, several building technologies have been explored in the described experimental set-up. In this chapter, the main findings extracted from the different experimental campaigns are provided and summarized, grouped by the different research fields. Finally, the limitations of this type of experimentation are identified and discussed.

3.1 Thermal insulation in building envelope as passive heating and cooling system

In this experimentation, cubicles from 8 to 11 (Figure 2), built during the second construction period, were used in order to test different passive insulation systems: 5 cm of polyurethane (9), 5 cm of mineral wool (10) and 5 cm of polystyrene (11). The same roof morphology is used in all cubicles. It is based on concrete precast beams slab insulated with 3 cm of polyurethane, finished with a cement mortar layer with an inclination of 3% and a double asphalt membrane. Figure 7 shows the construction details of the interface between facade and roof of insulated cubicles (Figure 7 b) and the cubicle without insulation, used as reference (Figure 7 a).

The experimentation carried out in 2008 was presented in Cabeza et al. [35], where cubicles mentioned before were tested under free floating and controlled temperature conditions using 24ºC as set point temperature.

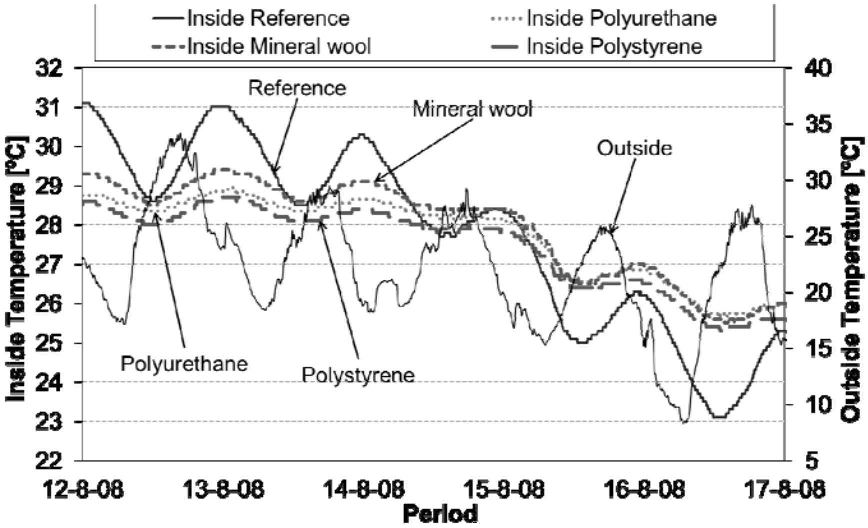


a) Reference cubicle (8) **b) Polyurethane (9), Mineral wool (10) and Polystyrene (11) cubicles**

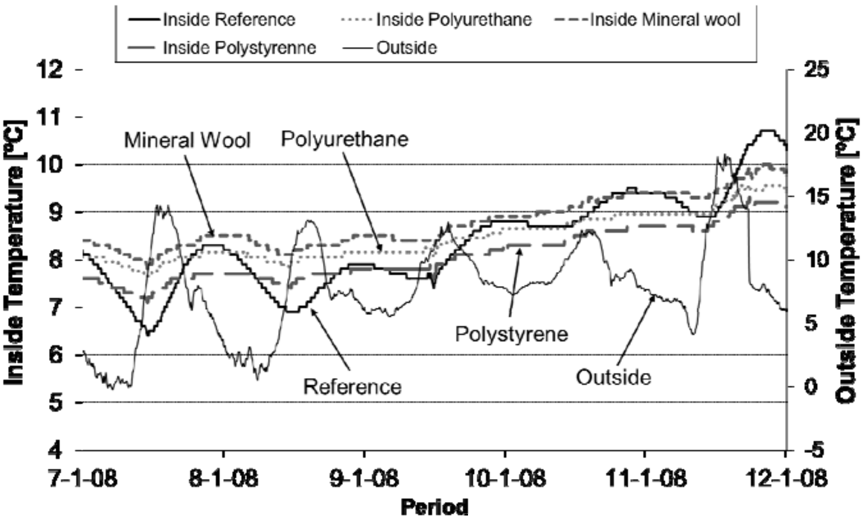
Figure 7. Construction systems details of non-insulated (a) and insulated cubicles (b) [35]

Results showed that, under free floating conditions (see Figure 8), all insulated cubicles experienced similar soft fluctuations during day-night periods (between 0.5ºC to 1ºC), while in the reference cubicle, these fluctuations are larger (between 1.5ºC to 2ºC) in both seasons, due to the lack of insulation.

Furthermore, the accumulated electrical energy consumption under controlled temperature conditions and hence the energy savings obtained by each insulated cubicle was also presented in Cabeza et al. [25]. During this experimentation, electrical oil radiators were used in winter and heat pumps in summer, both set at 24ºC. Table 1 shows a brief summary of the most representative results achieved in one week by the implementation of the different insulation materials.



a)



b)

Figure 8. Free floating experimentation in summer (a) and winter (b), 2008 [25]

Table 1. Weekly accumulated electrical consumption using 24ºC of set point and energy savings in summer and winter seasons (2008)

	Reference	Polyurethane	Mineral wool	Polystyrene
Summer [kWh]	8.3	3.5	4.5	5.1
Winter [kWh]	99.8	63.7	67.4	71.1

It can be noticed that PU cubicle presented the highest energy savings, being around 58% and 36% in summer and winter, respectively. On the other hand, differences between insulated cubicles were small, especially during summer, being the consumption of the polyurethane cubicle 18 % and 26 % smaller than MW and XPS cubicles, respectively.

The tested cubicles have been monitored since then in order to check possible degradation of insulation materials. Figure 9 compares the results from 2008 of weekly accumulated energy against the last results obtained in summer 2015 setting also heat pumps at 24ºC.

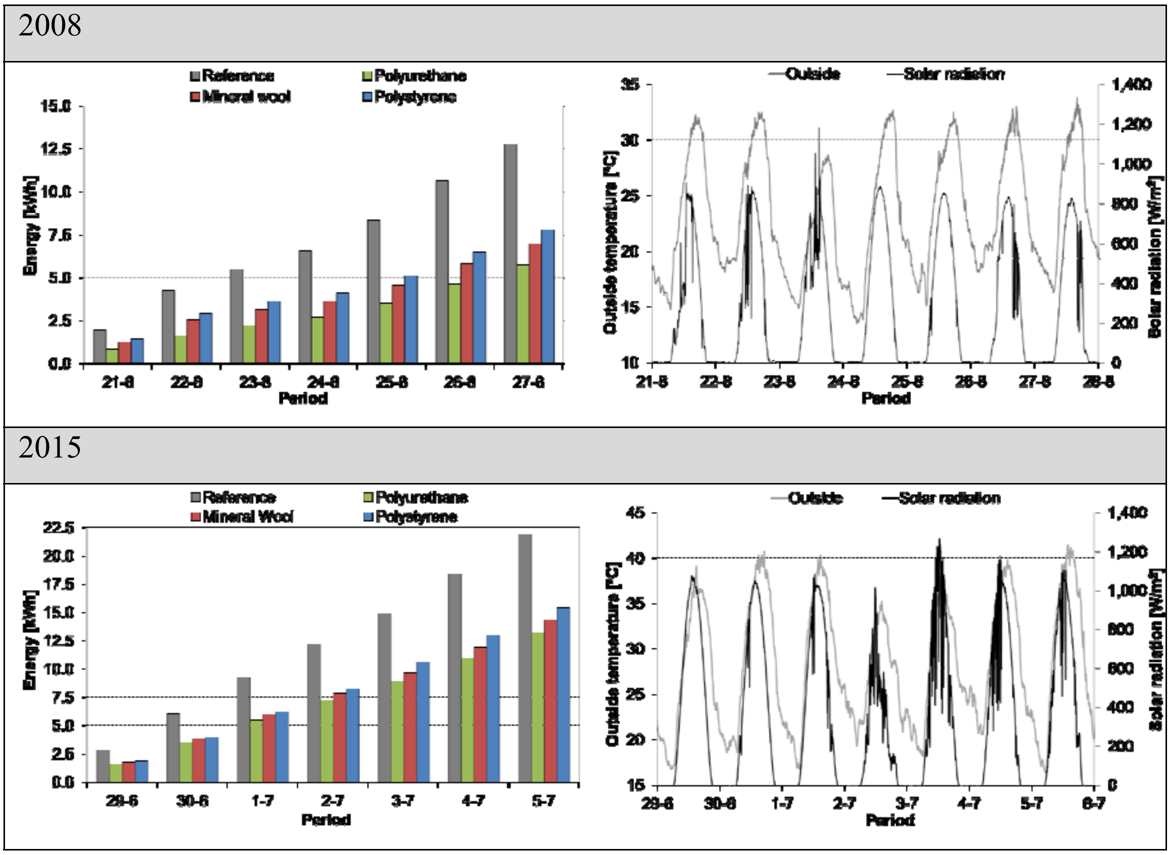


Figure 9. Comparison between results of summer 2008 and 2015 using a set point of 24ºC

Despite climatological conditions are different and, therefore, results of accumulated energy consumption are not similar, it can be noticed that results follow the same trend. Insulated cubicles present similar consumption, being the polyurethane cubicle the one which consumes less energy compared to mineral wool and polystyrene cubicles. Hence, there is no evidence that confirms the degradation of insulation materials in a 7-years period.

3.2 Dynamic performance of massive building envelope in comparison to high insulated wall

The aim of this research field was to evaluate the performance of two different envelope construction systems typical in the continental-Mediterranean area. As shown in Figure 10, system based on two layers of bricks, air gap and insulating layer is compared against a morphology based on a single layer of alveolar bricks, which is a 29 cm thick brick with a special design of holes that provides both thermal and acoustic insulation.

The cubicles used in this research according to Figure 2, were the cubicles with perforated brick morphology, 8, 9 and 10 (with no insulation, 5 cm of PU and 5 cm of mineral wool, respectively) and cubicle 15 with alveolar brick construction system. All cubicles have the same roof system based on concrete precast beams slab insulated with 3 cm of Polyurethane, finished with a cement mortar layer with an inclination of 3% and a double asphalt membrane.

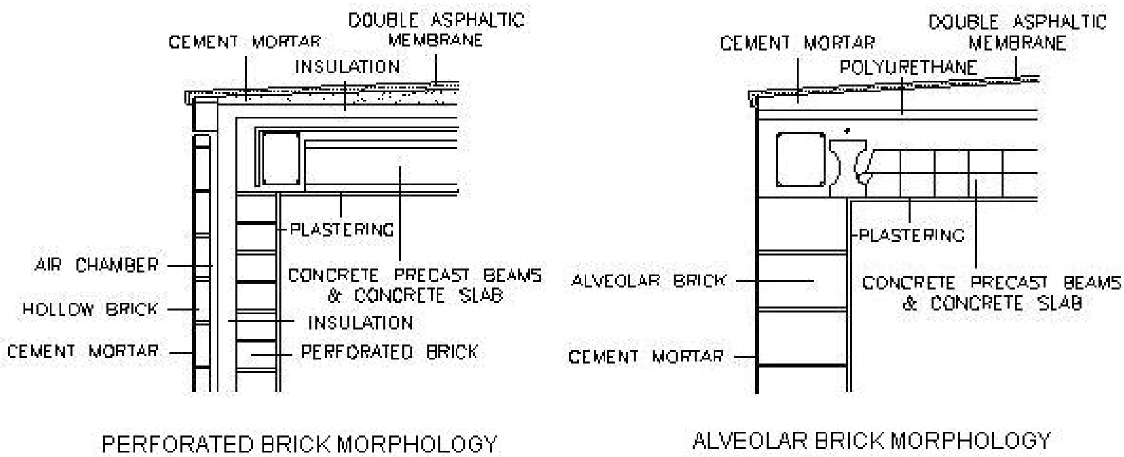


Figure 10. Sketch of tested construction systems [19]

The theoretical and experimental thermal transmittance in steady-state (U-value) of each envelope was calculated. According to de Gracia et al. [19 the insulated cubicles have U-value 45% lower in comparison to the alveolar one. However, the experimental campaigns of 2008 and 2009 demonstrated that these differences in thermal resistance were not reflected in the electrical energy required from HVAC to achieve desired set points. Thus, the alveolar cubicle only consumes averagely 2% and 13% more energy than the insulated ones during winter and summer periods, respectively. It can be noticed that there is a clear disagreement between the thermal resistance of the envelope and its real performance, which is caused in this case due to the thermal mass of the envelope, which is not considered in the U-value. A dynamic study based on the calculation of transient parameters such as thermal stability coefficient, thermal lag, decrement factor and thermal dynamic thermal transmittance confirms the hypothesis. This research concludes that it is crucial to include dynamic parameters in the evaluation of the performance of a building envelope or component. Nowadays, most of buildings standards just use U-value for the evaluation, which could lead to discard and underestimate several appropriate building designs.

3.3 Green infrastructure as building passive energy saving system

The research regarding green infrastructure is divided in two main topics. On the one hand, a long term study from 2009 to 2013 is focused on environmental and energy performance of two different extensive green roofs systems, and on the other hand, several studies from 2011 until 2016 are related to state of the art, vegetation, thermal behaviour and energy performance of Vertical Greenery Systems (VGS).

Regarding extensive green roofs topic, the first step was to evaluate the technical feasibility and the hydraulic capacity of the main materials, at laboratory scale [26], as well as measure the thermal performance of these systems at pilot plant scale [27. Furthermore, the possibility of reusing rubber from out use tires as drainage layer for extensive green roofs instead of the porous stone materials, currently used in some commercial solutions, was also studied. For this purpose, three cubicles were built and monitored in the experimental set-up (3, 4 and 15 according to Figure 2). Figure 11a, shows the morphology of these extensive green roofs cubicles, while Figure 11b shows the construction system implemented in the reference roof cubicle.

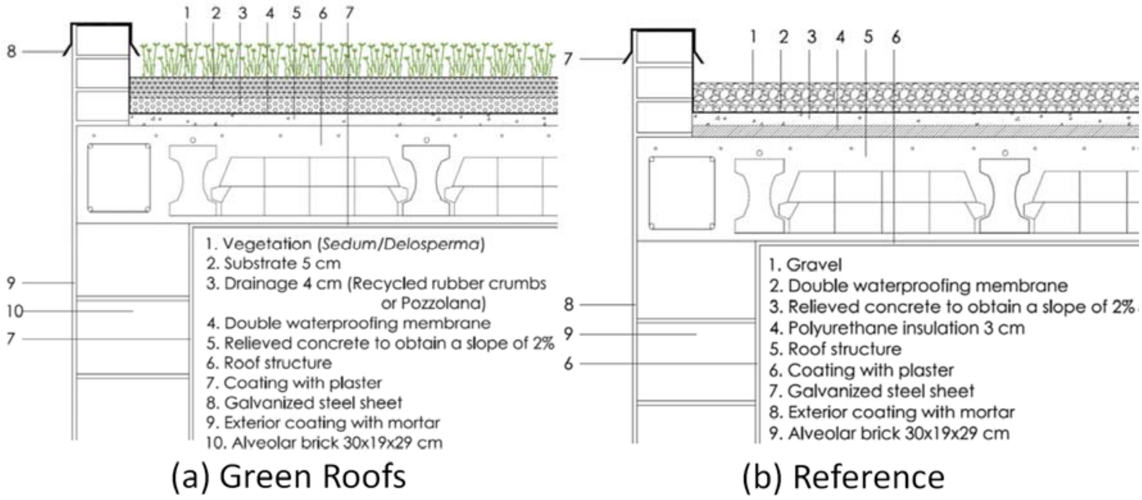


Figure 11. Detailed construction section of green roofs (a) and reference (b) roof cubicles [28

The thermal performance of extensive green roofs was measured at two stages of plant development, first with 20% of the roof surface coverage (summer 2011) 28 and then with more than 85% of the roof area covered (summer 2013) [29]. Experimental results showed that extensive green roof of 9 cm thickness provides energy savings under controlled temperature at 24 ºC during cooling periods even having only 20 % of the roof surface covered by plants. These results not only highlight the good performance of green roofs as passive tool for energy savings but the importance of substrate layer in this contribution.

In addition, due to the irrigation provided during the summer period to ensure the survival of plants, some differences were observed in the green roofs. Since pozzolana has higher water storage capacity than rubber crumbs, due to the micropores, a major development of foreign annual plants was observed which compete with *Sedum* and *Delosperma*. This fact implied a better development of *these species* in the rubber crumbs cubicle during the experimentation period. These species used for green roofs usually have a better behaviour in extreme conditions which may be an advantage for further maintenance and performance of the green roof.

Moving to the VGS topic, the first step consisted of evaluating the growth of four different climbing plants, the ability to provide shadow [30 as well as their potential as a passive energy saving system in Mediterranean continental climate. The four tested plants (Figure 12a from left to right) were Ivy (*Hereda helix*); Honeysuckle (*Lonicera* *japonica*); Boston Ivy (*Parthenocissus tricuspidata*); and Clematis (*Clemat*is *sp.*). This experimental research confirmed the potential as a passive tool for energy savings in buildings of green facades made with deciduous species, especially with Boston Ivy (*Parthenocissus Tricuspidata*). Hereafter, the selected vegetation was implemented at prototype scale to study the energy impact on a real building, as shown in Figure 12b. The extensive green facade was technically improved using a small and light mesh and was installed on East, South and West facades. Moreover, an intensive green wall system was also evaluated using another cubicle as shown in Figure 12c. The experimental facility was used to study the thermal and energetic performance, durability, feasibility and maintenance of the explained green facade and green wall systems in comparison to a reference cubicle. Experimental measurements show that during the cooling period, the electrical energy consumed by the HVAC system to achieve the desired comfort temperature (24 ºC) was reduced in both VGS when compared to the reference system. The achieved energy savings were around 33.9 % in case of extensive green facade and 59.9% in case of intensive green wall.

Figure 12 Selection of the climbing plant (a) and enhanced green facade system. Green facade (b) and green wall (c).

The presence of a light but steady breeze from the South-West direction slightly influenced the plant growth, generating areas with less dense foliage. This fact implies the necessity to consider deeply the wind influence in these studies. Furthermore, the influence of solar gains in the building during the periods of transition (spring and autumn) should be taken into account when working with deciduous plants, since they can grow and lose their foliage during different periods and at different rates.

Finally, in order to compare the different experimental studies around the world relating to GR and VGS, it must be taken into account that the most suitable data is the building wall/roof surface temperature under the green system, since it is the most representative value to quantify the capability of the green system to provide thermal improvements. It is important to highlight that these construction systems are variable in morphology, thickness, and materials depending on the country and, therefore, it could hinder the final thermal contribution provided by the green infrastructure.

3.4 Thermal performance of rammed earth used as a construction system

The aim of this research is to demonstrate that low embodied energy materials can be used instead of conventional ones (with higher embodied energy) and achieve similar thermal responses by adapting rammed earth walls to modern construction systems.

The comparison is done using, on the one hand, three cubicles built in the second construction period and using conventional construction systems: the reference (8), polyurethane cubicle (9) and polystyrene cubicle (11), and on the other hand, two rammed earth cubicles (13 and 14 according to Figure 2) built during the third construction phase. Cubicle 14 remains without insulation while cubicle 12 was recently insulated and coated. The construction systems are detailed as follows:

- Non-insulated Rammed Earth cubicle (14): Load-bearing rammed earth walls of 29 cm (with ground humidity protection of 19 cm composed by one row of alveolar brick and a polypropylene waterproof sheet).
- Insulated Rammed Earth cubicle (13): Same construction system than RE but walls are insulated with natural wood fibres panels of 6 cm (SYLVACTIS 140 SD ITE) and 1 cm of natural coating based on clay and straw (thickness < 2 cm).

Despite the experimentation with these cubicles is on-going, the first results of summer 2015 are presented here where free floating and controlled temperature experiments were performed at 21ºC (Figure 13).

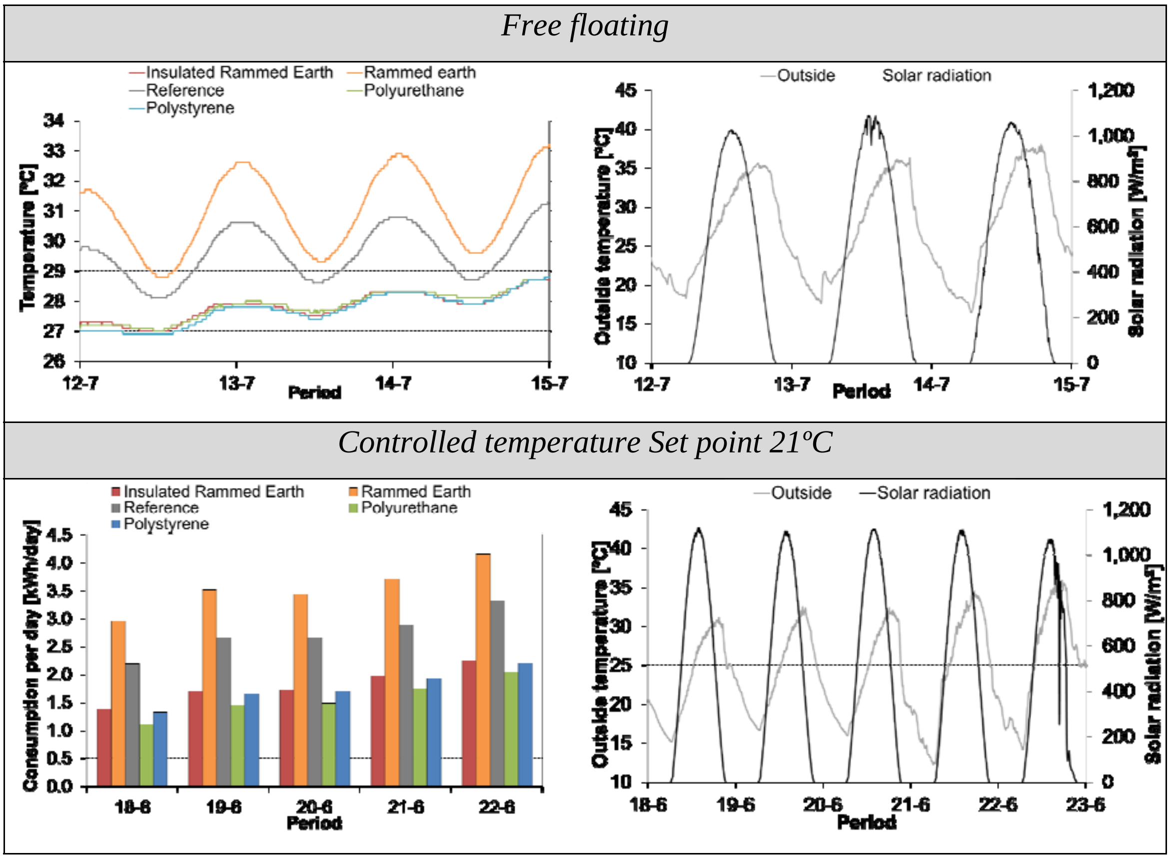


Figure 13. Results of experimentation in Summer 2015

Results show that the performance of the non-insulated rammed earth cubicle is notably worse than the reference cubicle due to the use of lighter roof structure and, especially, due to the thickness reduction of the rammed earth wall that increases heavily its thermal transmittance. In contrast, similar inner temperature profiles in free floating conditions as well as similar electrical energy consumption per day in controlled temperature are achieved by the implementation of wooden insulation panels on the outer face of the cubicle. The experimental results confirm the suitability of using sustainable construction systems and materials with low embodied energy instead of conventional ones since they can provide the same energy response when are implemented in buildings.

3.5 Use of PCM as passive cooling system

The inclusion of PCM as passive cooling system was done in three different construction typologies. First of all, the incorporation of micro-encapsulated PCM in concrete walls was tested. The thermal performance of a prefabricated concrete cubicle with 5% of PCM in weight was compared to a cubicle with the same characteristics but without PCM [31 (cubicles 1 and 2 according to Figure 2, respectively). The Micronal PCM embedded in the concrete with a phase change temperature of 26 ºC was designed to prevent high temperature peaks inside the cubicle during summer season and to smooth the internal ambient temperature. Experiments determined that the internal temperature profile had lower oscillations due to the PCM effect. In addition, in the concrete cubicle with PCM, two hours delay was registered in the maximum peak temperature.

Afterwards, the inclusion of PCM in brick construction systems was also studied. The macro-encapsulation in aluminium panels was chosen as the most feasible way to implement PCM within the different layers that composed these construction systems. On the one hand, in the typical Mediterranean brick system PCM macro-encapsulated (RT27) was added between the insulation and the internal part of the cubicle, and was compared to a cubicle without PCM (cubicles 12 and 9 according to Figure 2, respectively). On the other hand, the implementation of PCM panels (SP25) in alveolar brick system was also studied and compared to its reference [32 (cubicles 16 and 15 according to Figure 2, respectively). The inclusion of the PCM aluminium panels was done by mechanical fixing pieces that were made especially for this purpose. The panels were fixed by the corners taking care on not damaging the encapsulation.

In this experimentation, phase change materials were used to absorb the external heat loads of summer days and release it to outdoors during the night. Similarly to the concrete cubicles, free-floating experiments showed internal ambient temperatures profile with lower fluctuations in the cubicles with PCM. Nevertheless, during the hottest periods some problems were observed to achieve the PCM solidification.

Controlled temperature experiments were performed setting the same temperature in the heat pump of each cubicle. The energy consumed by the cooling system was registered and compared (Figure 14). The results demonstrated that the PCM cubicles reduced 15 % their energy consumption compared to the cubicles without PCM during the cooling period. The potential and contribution of the PCM as a passive cooling system in buildings was demonstrated by achieving significant energy savings and thermal comfort at building prototype scale.

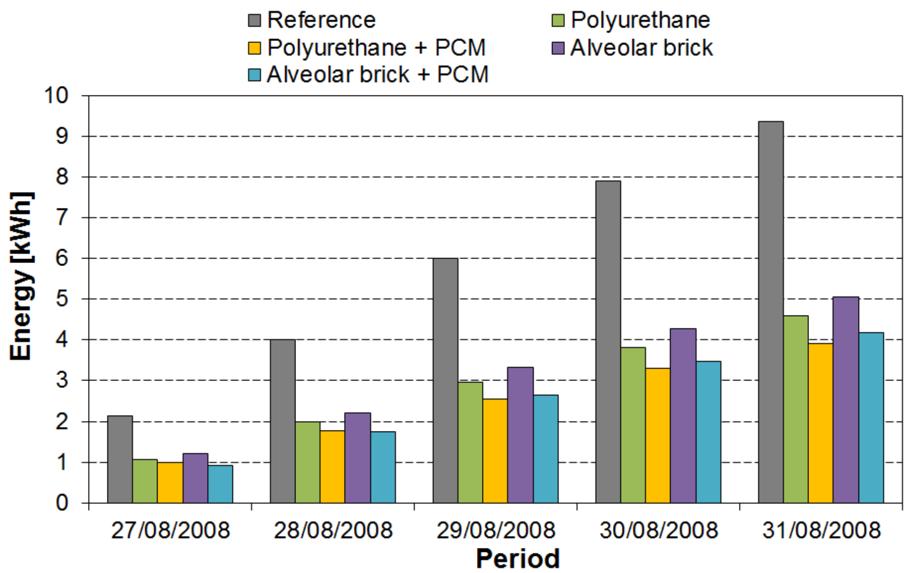


Figure 14. Accumulated energy consumption of brick systems cubicles under controlled temperature (24 ºC).

Finally, during the experimentation of the PCM macro-encapsulated cubicles some temperature sensors were placed inside the aluminium plates to register the PCM temperature. However, PCM leakage was detected through the sensors wire by capillarity. This problem can be solved by placing the data logger where the sensors are connected at a higher height than the location of the sensor.

3.6 Implementation of PCM as active system in building components

The experimental results demonstrated that the tested active technologies implementing PCM (ventilated facade and active slab with PCM) during winter can achieve important net energy savings for heating purposes. On the other hand, during summer, it was proved that the cold storage capacity of the systems is very sensitive to outer night temperatures, being limited under severe summer conditions. Hence, the use of these systems as a cold storage requires appropriate control strategies and the use of fans must be optimized to reduce the overall electrical energy consumption. Nevertheless, the experimental campaign showed the high potential of the night free cooling effect to cover partly the cooling demand.

Regarding the performance of the ventilated facade for heating, it was demonstrated that the use of this system can reduce the electrical energy required by the HVAC in 19% and 26% in comparison to the reference, when programmed to maintain a set point of 21ºC and 19ºC, respectively [20. Moreover, the system has been tested with natural and mechanical heating discharges (natural convection or with use of fans), showing that the use of mechanical ventilation provides the same net energy savings than the natural discharges and is unnecessary unless a fast heating supply is required by the demand. Finally, the winter tests confirmed that the use of SP-22 as PCM limits the potential of the system, since its low melting range (20 to 22ºC) makes difficult to use the latent heat for heating purposes. Higher melting temperatures would be recommended for the application of this technology for heating purposes.

On the other hand, the performance of the ventilated facade with PCM during summer as a cold storage system did not achieve net electrical savings. When using SP-22 as PCM, the electrical savings achieved in the HVAC do not compensate the consumption of the fans (which are required to solidify the PCM during night-time and cooling discharge in daytime). The fans used in the building prototype were oversized to its functionality and there is a high margin to reduce the electrical energy consumed for providing mechanical ventilation by using less powerful fans. Moreover the use of SP-22 limits strongly the possibility of using the system as cold storage, since the hysteresis presented by the material (melting ~22ºC and solidification ~ 18ºC) makes very difficult to fully solidify the material using low temperatures at night. Moreover, the presence of thermal bridges in the outer skin leads to low storage efficiencies (below 10%) [21. After the first summer experimental campaign in 2012, the thermal bridges were addressed and PCM was replaced for RT21. New experimental campaign in 2014 showed storage efficiencies between 50 and 60% [35. In addition, the use of RT-21 led to a reduction of 29.3% in the energy consumed by the heat pump installed in the cubicle with the ventilated facade in comparison to the reference. As shown in Figure 15, the system has a higher potential in providing free cooling, which is altogether with the potential in providing cooling from storage, very sensitive to temperature at night. It has been also demonstrated experimentally that apart from the free cooling and cold storage effect, the ventilated facade presents another thermal benefit to the building, which is the overheating prevention during peak load hours due to proper ventilation in the ventilated cavity.

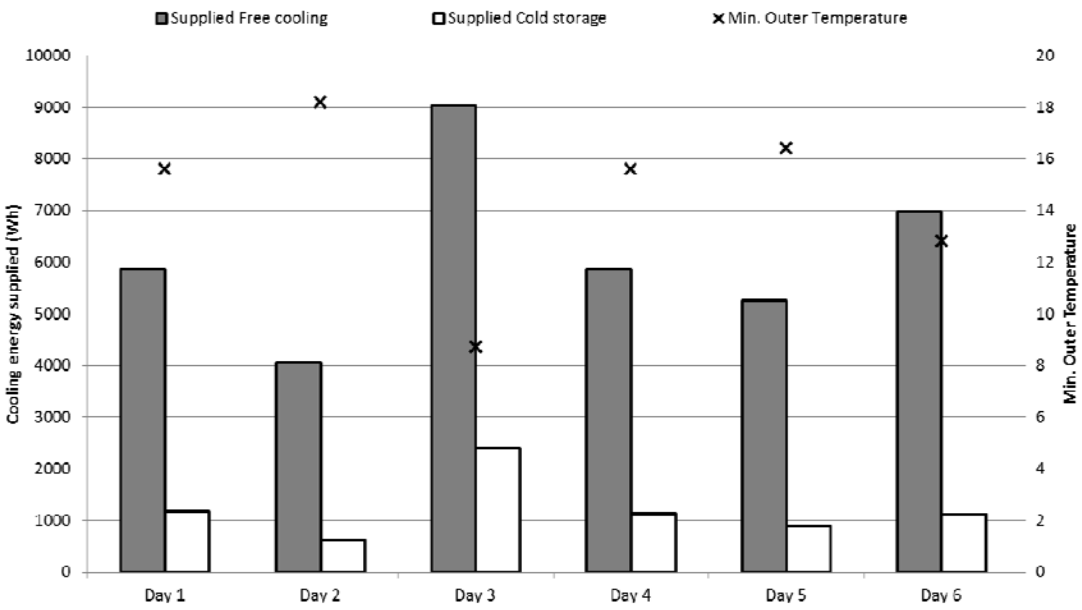


Figure 15. Energy discharged during free cooling and cold storage during June 2014.

Concerning the testing of the active slab technology, summer experiments showed the cold storage potential of the system. Significant energy savings between 30% and 50%, depending on the weather conditions, were registered in the active slab cubicle compared to the reference cubicle for the experiments performed under mild summer conditions. However, during severe summer conditions, outside minimum temperatures during night time were registered around 19 ºC which makes difficult to solidify the PCM. Therefore, the energy savings achieved in the active slab cubicle under these conditions were about 15 % compared to the reference one [34. Although the active slab reduces the heat pump consumption achieving energy savings, the high energy consumed by the fan did not compensate the savings. Hence, the energy consumed by the fan is critical to achieve net energy savings as occurred in the case of the ventilated facade. This issue could be also addressed by replacing the fan for a more efficient one, or even combining with cold passive discharge sequences, which was shown to be an interesting alternative.

In addition, the free cooling potential was demonstrated to cool down the internal ambient and keep it cooler at the beginning of the next day. Furthermore, the control system that manages the operation of the active slab depending on temperatures and energy requirements could be improved to be more accurate and optimize the fan operation, e.g. by the addition of weather forecast control for the operation of the next day.

On the other hand, the winter performance of the active slab was also tested. As it was previously mentioned, a solar air collector was installed in the south facade of the active slab cubicle to melt the PCM. Mainly two types of control strategies were programmed, each of them tested under different weather scenarios (severe or mild winter conditions, sunny or cloudy). First strategy was the “heat storage” test which consisted of melting the PCM during daytime and storing the heat absorbed, and providing heating to the internal ambient of the cubicle once there is no more sunlight. The heat pumps of the active slab and reference cubicle were set at 18 ºC and their energy consumption was compared. Results presented in Figure 16 show that in experiments where a complete PCM melting was achieved, the active slab cubicle registered between 48% and 60% of energy savings compared to the reference one. Moreover, in experiments where PCM was not melted or partially melted, the active slab cubicle reduced its energy consumption by 11 % and 26 %, respectively. The second strategy tested was the “day discharge”, in which the active slab supplied heat during daytime, in case the PCM temperature is higher than the internal ambient temperature. Active slab cubicle with “day discharge” experiments achieved 26 % and around 45 % of energy savings compared to the reference one under severe and mild winter conditions, respectively.

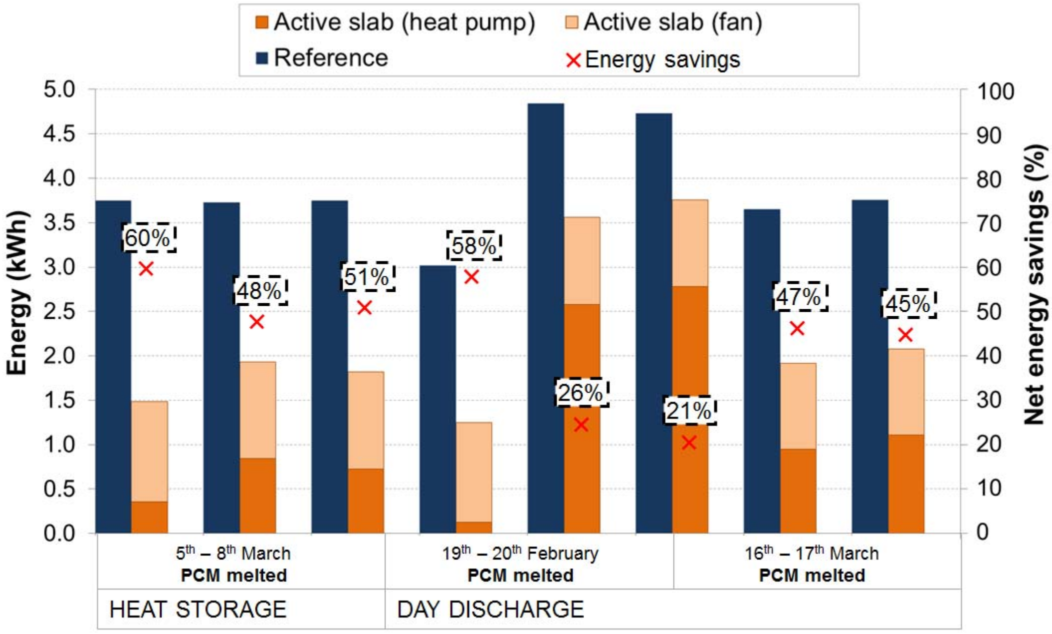


Figure 16. Electrical energy consumption of the heat pumps of the reference and active slab cubicle during Heat storage and Day discharge experiments (active slab heating mode) [34

The active slab technology tested presented some drawbacks that appeared during the testing. First, the air tightness of the gates used in the air duct installation is very important to ensure the heat losses reduction. Moreover, the temperature sensors used in the control system should be clearly selected. In this case, the PCM temperature sensor was especially important since not all the PCM included in the slab performed the same way (melting and solidification).

3.7 Implementation of building integrated active systems

The radiant wall coupled to a geothermal system showed good energy savings in both summer and winter seasons. Furthermore, the test proved the peak load shifting capability of the radiant wall. However, the tests also showed the limited cooling capacity of the free-cooling mode and the difficulty to optimize the control strategy in both cooling and heating periods.

In controlled temperature tests in free-cooling mode, the radiant wall cubicle achieved savings of 54 % and 82 % at set-points of 24ºC and 26ºC respectively [23. However, at set-point 22ºC, the radiant cubicle used more energy than the references equipped with conventional air-to-air heat pumps. That was caused by the limited supply temperature, as the ground was at 17ºC, the supply temperature provided by the boreholes was close to the set-point temperature. To offset this short temperature gradient the system operated during longer periods, and thus it consumed more energy.

The night-time operation test showed the capability of the radiant wall for thermal energy storage. Cooling during the night at a low set-point allowed the cubicle to maintain the indoor temperature at the comfort range during the day without requiring additionally cooling. In contrast, the reference cubicles were unable to store energy in the walls, and thus these were at a higher temperature than the indoor air. Therefore, as soon as the cooling was stopped the heat of the wall was released to the indoor ambient, rapidly increasing the air temperature.

The radiant wall also showed good energy savings for heating purposes, with a minimum of 20 % of energy savings in the worst operation conditions [24. Moreover, the energy savings were less sensitive to set-point temperature than in cooling mode and the heat pump achieved a very stable coefficient of performance at all set-points.

The peak load shifting was also tested in the heating mode. In these test the radiant cubicle had a pre-heating period in the night in which the set-point temperature was 26ºC, while during the rest of the day the set-point was 22ºC. As the references could not store energy the set-point temperature for them was constant, being 22ºC and 24ºC for each. The test showed that the radiant wall cubicle energy savings were lower than the results from controlled temperature test. Despite this, the operation cost savings were significantly higher than the energy savings. Finally, the tests showed that the length of the pre-heating period was critical to optimize the control. Long pre-heating periods resulted in the cubicle requiring reheating in order to maintain the high set-point temperature, and thus energy was wasted. On the other site, short pre-heating could not store enough heat, therefore heating was required during the rest of the day to maintain the comfort conditions.

3.8 Limitations and advices

As it was previously stated, certain limitations and difficulties have been identified after several experimental campaigns conducted in the set-up. In this section, the authors want to share the experience and provide useful information for researchers who want to use this type of experimental set-up in the future.

Regarding the methodology, it compares the performance of different technologies under real environmental conditions, which are not possible to control. Hence, it is difficult to compare results within different years, which might be very useful to analyse the performance of certain material such as insulation through the years. Continuous validation of numerical tools would be a possible methodology to analyse the variation in the performance of such materials or systems.

Furthermore even one of the main benefits of using a building prototype scale for testing a technology is that the influence of the tested material and/or technology in the performance of the building can be specifically determined and quantified. However, in some cases there are difficulties to quantify the energy savings contribution related to each thermal mechanism involved. For example, in the experimental testing of green infrastructures it was difficult to quantify the effect of the evaporation from soil, plant transpiration, insulation from substrate, thermal inertia of different layers, water moisture content, etc. Moreover, the shape factor and dimensions of the prototypes makes that the roof have a strong influence in their thermal performance.

Moreover, the ventilation plays an important role in such small test cubicles. The impact of different ventilation strategies in the different tested technologies has not been explored yet. Moreover, the infiltration in the tested cubicles has not been possibly measured since most of infiltrations occur at the door. The device used for testing infiltration (blower-door), which is installed at the door of a house, is capable of inducing a range of airflows sufficient to pressurize and depressurize the room. For this reason, doors, and components required for installing equipment (such as heat pumps or sensors) have been air-tightened. Nevertheless, the impossibility of measuring infiltration rate makes very difficult to use the experimental data to validate building simulation models, such as those developed using EnergyPlus.

Regarding the acquisition of data, as it was previously detailed in section 2.1, each test cubicle has multiple data logger devices, which are connected to a main signal cable and send the information to the data acquisition centre. This signal cable has to cover a long distance (over 100 m). No problem was found when having few test cubicles, and hence data logger devices, but after 2009, when the facility grew from 9 to 21 test cubicles, the signal cannot be transferred successfully to the data acquisition centre and two signal relays (AC-200 from Step.SL) had to be connected in the signal path in order to be able to communicate data.

Furthermore, in the evaluation of the performance of the tested passive systems, heat flux meters were installed in the south wall in order to measure the heat absorption and release through this component. However, the envelopes are usually insulated and the measured values of heat flux are usually between the range -5 to +5 W/m^2. The used sensors (HUKSEFLUX HFP01) had a resolution of 1 W/m^2, which is not enough for measuring adequately the heat flux through walls.

The use of commercial available heat pumps limited the flexibility of testing. The controllers of the heat pumps had few adjustable parameters, mainly set-point temperature and fan speed. Furthermore, these controllers did not include scheduling that allowed for variable conditions depending on day time. Finally, the data of the in-built sensors and the status parameters of the controllers could not be registered by any means, limiting the knowledge and interpretation of the heat pumps performance.

Finally, another limitation regarding the used equipment is that it was not possible to use heat pumps during certain heating periods due to high outer humidity, which caused icing in the evaporator. During these weeks, electrical oil radiators were used for providing heating, however, it was found more difficult to control the set point using these heating systems rather than when using heat pumps.

4. Conclusions

This paper presents the methodology and main results extracted from a building prototype experimental set-up located at Puigverd de Lleida. The test facility is used to experimentally investigate different materials, technologies and systems which are integrated as passive and/or active systems in the building design aiming to provide energy savings for space heating and cooling under Csa (warm temperate, dry and hot summer) climate. This set-up consists of 22 building prototypes and has followed a comparative methodology during its different experimental campaigns and research fields since 2002. The comparative studies allow analysing the effect of each tested technology in the energy performance of the building when compared to a reference, which is an exact building prototype as the analysed, but without the tested technology.

Regarding the research fields related to passive systems, the set-up has been used to quantify the savings due to the use of insulation in building envelope, as well as to explore the effect of adding different types of insulation and their possible degradation over the time. Moreover, different construction systems and morphologies have been compared, proving the good performance of more sustainable construction materials and options, while highlighting the necessity of including thermal inertia in the building regulation codes in order to not underestimate suitable construction designs. Furthermore, the experimental facility has been used to test different green infrastructures, such as green roofs, green walls and green facades, evaluating their effect both in summer and winter periods. Finally, phase change materials which are considered innovative materials for the building sector have been tested at building prototype scale for passive cooling, being integrated in the envelope both micro and macro-encapsulated.

In addition, two different active systems implementing PCM for energy savings were tested at the experimental set-up: a ventilated facade with PCM in its air chamber and an active slab with PCM inside its hollows. Both systems can be used to provide heating during winter and cooling during summer. Their operating principle during winter are based on storing solar radiation through the melting process of PCM and discharge it to the inner environment, while during summer, it uses low temperature at night to solidify the PCM and provide a cooling supply during daytime. The tested active systems have demonstrated their potential to provide savings both in winter and summer seasons, however, several design and control aspects should be further investigated in order to become competitive technologies at market level.

A third active system was tested, a radiant wall coupled to a ground source heat pump for heating and to a ground heat exchanger for cooling. The operating principle was to exploit the big surface of the radiant wall to allow high temperature cooling and low temperature heating. Moreover, the radiant wall was capable of peak load shifting capability. The system showed good savings in both heating and cooling mode. Furthermore, the peak load shifting capability reduced operation cost beyond energy savings. However, optimized control was required to exploit the full potential of the radiant wall.

Finally, the authors identified the problems and limitations of this type of experimental methodology and share them to provide advices and useful information for researchers who want to use this type of experimental set-up in the future.

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References

1 Directive 2010/31/EU of the European parliament and of the council of 19 May 2010 on the energy performance of buildings. Available from: http://www.epbd-ca.eu.

2 International Energy Agency. Energy Technology Perspectives 2012. Pathways to a Clean Energy System. France, 2012.

3 J.S. Sage-Lauck, D.J. Sailor, Evaluation of phase change materials for improving thermal comfort in a super-insulated residential building, Energy and Buildings. 79 (2014) 32–40.

4 N.N. Maeus, A. Pinto, G. Carrilho, Validation of EnergyPlus thermal simulation of a double skin naturally and mechanically ventilated test cell. Energy and Buildings 75 (2014) 511-522.

5 T. Kobari, J. Okajima, A. Komiya, S. Maruyama, Development of guarded hot plate apparatus utilizing Peltier module for precise thermal conductivity measurement of insulation materials. International Journal of Heat and Mass Transfer 91 (2015) 1157-1166.

6 O. Doutres, N. Atalla, Experimental estimation of the transmission loss contributions of a sound package placed in a double wall structure. Applied Acoustics 72 (2011) 372-379.

7 M.S. Amin, S.M.A. El-Gamal, F.S. Hashem, Fire resistance and mechanical properties of carbon nanotubes – clay bricks wastes (Homra) composites cement. Construction and Building Materials 98 (2015) 237-249.

8 I. Visa, A. Duta, M. Comsit, M. Moldovan, D. Ciobanu, R. Saulescu, B. Burduhos, Design and experimental optimisation of a novel flat plate solar thermal collector with trapezoidal shape for facades integration. Applied Thermal Engineering 90 (2015) 432-443.

9 J. Dong, Z. Zhang, Y. Yao, Y. Jiang, B. Lei, Experimental performance evaluation of a novel heat pump water heater assisted with shower drain water. Applied Energy 154 (2015) 842-850.

10 A.S. Andelkovic, B. Gvozdenac-Urosevic, M. Kljajic, M.G. Ignjatovic, Experimental research of the thermal characteristics of a multi-storey naturally ventilated double skin façade. Energy and Buildings 86 (2015) 766-781.

11 T. Cholewa, A. Siuta-Olcha, Long term experimental evaluation of the influence of heat cost allocators on energy consumption in a multifamily building. Energy and Buildings 104 (2015) 122-130.

12 European Commission Decision C. Horizon 2020 – Work Program 2014-2015. General Annexes G.

13 G.M. Revel, M. Martarelli, M. Emiliani, L. Celotti, R. Nadalini, A. De Ferrari, S. Hermanns, E. Beckers, Cool products for building envelope – Part II: Experimental and numerical evaluation of thermal performances. Solar Energy 105 (2014) 780-791.

14 I. Mandilaras, I. Atsonios, G. Zannis, M. Founti, Thermal performance of a building envelope incorporating ETICS with vacuum insulation panels and EPS. Energy and Buildings 84 (2014) 654-665.

15 R. Albatici, A. M. Tonelli, M. Chiogna, A comprehensive experimental approach for the validation of quantitative infrared thermography in the evaluation of building thermal transmittance. Applied Energy 141 (2015) 218-228.

16 R. Li, Y.J. Dai, R.Z. Wang, Experimental and theoretical analysis on thermal performance of solar thermal curtain wall in building envelope. Energy and buildings 87 (2015) 324-334.

17 C. Li, J. Tan, T.T. Chow, Z. Qiu, Experimental and theoretical study on the effect of window films on building energy consumption. Energy and buildings 102 (2015) 129-138.

18 M.J. Kottek, J. Grieser, C. Beck, B. Rudolf, F. Rubel, World map of Köppen–GeigerClimate classification updated, Meteorologische Zeitschrift 15 (2006) 259–263.

19 A. de Gracia, A. Castell, M. Medrano, L.F. Cabeza, Dynamic thermal performance of alveolar brick construction system. Energy conversion and management 52 (2011) 2495-2500.

20 A. de Gracia, L. Navarro, A. Castell, A. Ruiz-Pardo, S. Álvarez, L.F. Cabeza, Experimental study of a ventilated facade with PCM during winter period. Energy and Buildings 58 (2013) 324-332.

21 A. de Gracia, L. Navarro, A. Castell, A. Ruiz-Pardo, S. Álvarez, L.F. Cabeza, Thermal analysis of a ventilated facade with PCM for cooling applications. Energy and Buildings 65 (2013) 508-515.

22 L. Navarro, A. de Gracia, A. Castell, S. Álvarez, L.F. Cabeza, PCM incorporation in a concrete core slab as a thermal storage and supply system: Proof of concept. Energy and Buildings 103 (2015) 70–82

23 J. Romaní, G. Pérez, A. de Gracia, Experimental evaluation of a cooling radiant wall coupled to a ground heat exchanger, Energy and Build., 129 (2016) 484-490

24 J. Romaní, G. Pérez, A. de Gracia, Experimental evaluation of a heating radiant wall coupled to a ground source heat pump, Renew. Energy, 105 (2016) 520-529

25 L.F. Cabeza, A. Castell, M. Medrano, I. Martorell, G. Pérez, I. Fernández. Experimental study on the performance of insulation materials in Mediterranean construction. Energy and Buildings 42 (2010) 630-636.

26 A. Vila, G. Pérez, C. Solé, A.I. Fernández, L.F. Cabeza, Use of rubber crumbs as drainage layer in experimental green roofs. Building and Environment 48 (2012) 101-106.

27 G. Pérez, A. Vila, L. Rincón, C. Solé, L.F. Cabeza, Use of rubber crumbs as drainage layer in green roofs as potential energy improvement material. Applied Energy 97 (2012) 347-354.

28 J. Coma, G. Pérez, A. Castell, C. Solé L.F. Cabeza, Green roofs as passive system for energy savings in buildings during the cooling period: use of rubber crumbs as drainage layer. Energy Efficiency 7 (2014) 841-849.

29 J. Coma, G. Pérez, C. Solé, A. Castell, L.F. Cabeza, Thermal assessment of extensive green roofs as passive tool for energy savings in buildings. Renewable Energy 85 (2016) 1106-1115

30 G. Pérez, L. Rincón, A. Vila, J.M. González, L.F. Cabeza, Green vertical systems for buildings as passive systems for energy savings. Applied Energy 88 (2011) 4854-4859.

31 L.F. Cabeza, C. Castellón, M. Nogués, M. Medrano, R. Leppers, O. Zubillaga. Use of microencapsulated PCM in concrete walls for energy savings. Energy and Buildings 39 (2007) 113-119.

32 A. Castell, I. Martorell, M. Medrano, G. Pérez, L.F. Cabeza. Experimental study of using PCM in brick constructive solutions for passive cooling. Energy and Buildings 42 (2010) 534-540.

33 L. Navarro, A. de Gracia, A. Castell, L.F. Cabeza. Thermal behaviour of insulation and phase change materials in buildings with internal heat loads: experimental study. Energy Efficiency 8 (2015) 895-904.

34 L. Navarro, A. de Gracia, A. Castell, L.F. Cabeza. Experimental evaluation of a concrete core slab with phase change materials for cooling purposes. Energy and Buildings (2016)

35 A. de Gracia, L. Navarro, A. Castell, L.F. Cabeza, Implementation of a control system in a ventilated facade with PCM. In proceedings 9th International Renewable Energy Storage Converence (IRES 2015) Düsseldorf, March 9-11, 2015.